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RANGE-ENERGY RELATIONS FOR PROTONS AND ELECTRONS IN Al, Si, and SiO_2

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CONTENTS

ABSTRACT

Range-energy relationships for protons penetrating silicon and quartz are presented for the energy region 100 kev to 100 Mev. The range of protons in Si is obtained from range data in Al, corrected by the inverse mass stopping power ratio of the two elements. Low energy data (100 kev to 1 Mev) for Al are recalculated by graphical integration of the reciprocal mass stopping power curve. Ranges in Al for protons greater than 1 Mev in energy are taken from the literature. The data for SiO_2 are calculated from data on Si and gaseous O_2, based on Bragg's rule that the stopping power of a compound is equal to the sum of the contributions made by the individual atoms of the compound. To complete the picture, range-energy relationships for electrons are also presented.

PROBLEM STATUS

This is a final report on one phase of the problem; work on the problem is continuing.

AUTHORIZATION

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INTRODUCTION

Recent interest in the effects of charged particle radiation on silicon solar cells, and in the extent of protection afforded by varying thicknesses of quartz covers, has drawn attention to the lack of readily available range-energy data for both Si and SiO_2. Present practice is to assume that range-energy data for Al is not greatly different from that which should apply to these materials. While this is a reasonable assumption, a certain degree of approximation is still involved. In addition, it is desirable to re-examine the validity of the Al data for protons below 1 Mev.

In this report, range-energy relationships for protons penetrating Si and SiO_2 are calculated for the energy region above 100 kev. The data for Si are obtained from data on Al, corrected by the relative mass stopping power of the two elements. Low energy data for Al are recalculated by integration of the reciprocal mass stopping power curve. The data for SiO_2 are obtained from data on Si and gaseous O_2, based on Bragg's rule that the stopping power of a compound is equal to the sum of the contributions made by the individual atoms of the compound.

To complete the picture, range-energy relationships for electrons are also presented.

THEORY

Charged particles in passing through matter lose energy predominantly through inelastic collisions with atomic electrons. For heavy charged particles, the energy loss per unit path length can be calculated from the following expression (Ref. 1):

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{mv^2} N \left\{ Z \left[\ell n \frac{2mv^2}{I} - \ell n (1 - \beta^2) - \beta^2 \right] - \sum_i C_i \right\} \tag{1}$$

where ze is the charge of the incident particle and v its velocity, m is the rest mass of the electron, N is the number of stopping atoms per cubic centimeter of material and Z their atomic number, I is the average excitation potential of an electron of the absorbing material; β is a relativistic correction term equal to v/c, and the C_i terms are shell corrections for less effective stopping by electrons of the ith shell because of binding effects. The term $-dE/dx$ is also known as the stopping power of the absorbing material. The mass stopping power $_m(-dE/dx)$, or energy loss per gram per cm^2 of absorbing material, is equal to $(-dE/dx) \times (1/\rho)$, where ρ is the density of the material.

For electrons, the energy loss equation is (Ref. 2):

$$-\frac{dE}{dx} = \frac{2\pi e^4 NZ}{mv^2} \left[\ell n \frac{mv^2 E}{2I^2 (1 - \beta^2)} - \ell n\, 2 \left(2\sqrt{1 - \beta^2} - 1 + \beta^2 \right) + (1 - \beta^2) + \frac{1}{8} \left(1 - \sqrt{1 - \beta^2} \right)^2 \right]. \tag{2}$$

The reciprocal of the stopping power (RSP) is equal to the differential track length, or distance traveled per unit energy interval. The quantity dx thus represents the average distance traveled by the particle in losing an amount of energy dE. Integrating over the entire energy range then gives the mean distance traveled by the particle before it comes to rest:

$$R_{RSP} = \int_0^E \left(-\frac{dx}{dE}\right) dE. \tag{3}$$

This quantity is known as the reciprocal stopping power range. Since -dx/dE tends to become infinite as E approaches zero, the usual practice is to integrate between limits:

$$R_{RSP} = \int_{E_0}^E \left(-\frac{dE}{dx}\right) dE + R_0 \tag{4}$$

where R_0 is determined from experimental data. If experimental data on R_0 are not available, a close approximation to R_{RSP} can be obtained by plotting -dx/dE vs E, extrapolating the curve to zero energy, and integrating graphically. The error involved in the extrapolation is generally quite small except for the range values at very low energies; since these ranges are quite short, any errors will have a negligible effect on the range values at higher energies.

It should be noted that the RSP range, or path length, is not the same as the thickness of absorber required to stop a charged particle. On the average, a large number of small-angle scattering processes accompanies any appreciable energy loss experienced by the particle. The cumulative effect of this multiple scattering results in the total path length being greater than the actual thickness of material traversed. Calculated RSP ranges will therefore always exceed the actual ranges measured experimentally. For protons, this difference is quite small, since an energetic proton travels in essentially a straight line for the greater portion of its path. For electrons, however, the difference can be appreciable, since the much smaller mass of the electron results in many more scattering processes for a given energy loss. In fact, the total path length of electrons within an absorber may be as much as 2 to 4 times the actual thickness of absorber required to stop them. For this reason, calculated R_{RSP} values for electrons will give erroneous results when used to estimate the stopping thickness of a material.

Statistical fluctuations in the energy loss per collision result in a spread in the range values for individual particles. This spread is known as straggling. In the case of an initially monoenergetic beam of protons, a plot of the number of protons penetrating into a material versus distance penetrated shows clearly that the ranges of all the particles are not exactly the same (Fig. 1). This straggling effect for protons is quite small, generally of the order of 1 to 2% for initial energies in the vicinity of 1 Mev. However, as a result of this straggling, it is possible to obtain three different range values, depending on how the data is interpreted. The mean range R_m is defined as the thickness of material at which 50% of the particles have been stopped. The extrapolated range R_{ex} is obtained by extrapolating the straight portion of the curve to zero. The maximum range R_{max} is the thickness of absorber which stops 100% of the particles. Although extrapolated ranges are often reported in the older literature, the mean range is what is generally used at the present time. The RSP range as calculated from Eq. (4) also represents a mean value. Whenever range values are reported, it is important to specify which range is meant.

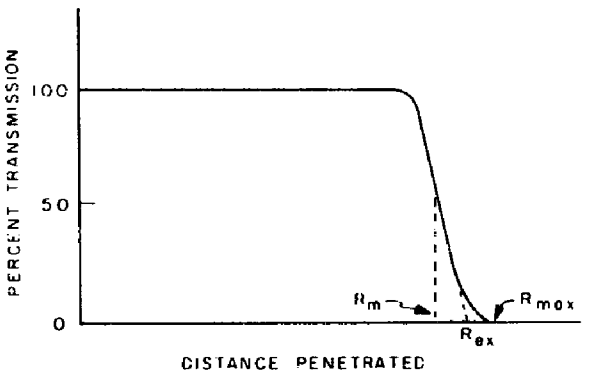

Fig. 1 - Typical number-distance curve for protons. R_m is the mean range, or thickness which just stops 50% of the protons; R_{ex} is the extrapolated range; R_{max} is the maximum range, or thickness which just stops 100% of the protons.

The effect of multiple scattering and energy loss straggling is much more pronounced in the case of electrons. It has been pointed out above that calculated path lengths (R_{RSP}) in the case of electrons are of little use in estimating the thickness of absorber which will reduce the transmitted beam intensity to zero. The latter value must be determined empirically. If an initially monoenergetic beam of electrons is allowed to penetrate various thicknesses of absorber, the number of electrons emerging from the absorber is seen to be a steadily decreasing function of absorber thickness (Fig. 2), unlike the case of protons. Near the end of the absorption curve, there is a pronounced tail merging into a weak background. The point at which the tail disappears into the background is known as the maximum range R_{max}. Because of the difficulty in making an accurate estimate of R_{max}, it is more convenient to extrapolate the linear portion of the curve to where it meets the background. This is known as the practical range R_p and is the range which is generally used in the case of electrons.

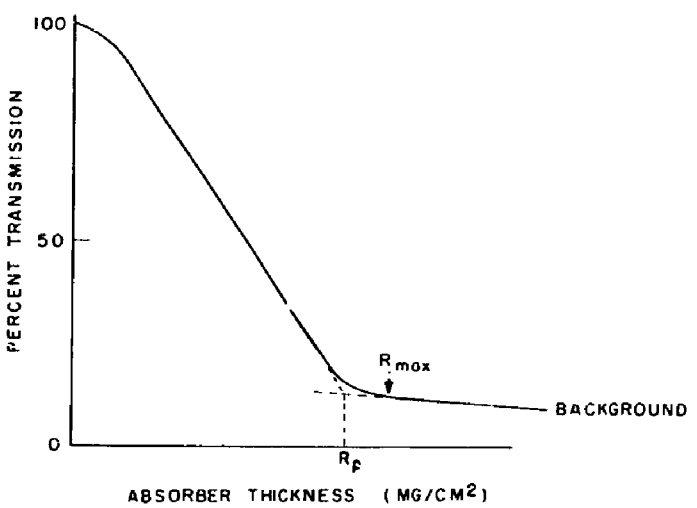

Fig. 2 - Absorption curve for a monoenergetic electron beam in aluminum. R_p is the practical range, determined by extrapolation of the linear curve to where it intersects with the background; R_{max} is the maximum range, determined by the point where the absorption curve merges with the background.

Much of the available range-energy data for electrons is based on β-ray measurements. Because of the continuous spectrum of energies involved in β-emission, there is no linear portion of the absorption curve (although in some cases it is approximately so when plotted on a semilog scale), and a linear extrapolation is not possible. However, various techniques have been developed (such as the Feather comparison method) by which the range R_β corresponding to the maximum β-ray energy can be calculated. As will be shown later, experimental data indicate there is no significant difference between the range R_β of a β-emitter and R_p of a monoenergetic electron beam with initial energy equal to the maximum β energy. This fact is utilized in constructing a range-energy curve for electrons.

METHODS AVAILABLE

From the brief summary above, it is evident that three different approaches can in principle be used to obtain range-energy relationships.

Theoretical Calculation of R_{RSP}

The first approach is a theoretical calculation of $-dE/dx$ from Eqs. (1) or (2), followed by integration according to (3) or (4) to give a reciprocal stopping power range. In the case of protons, Eqs. (1) and (4) have been the basis of the well-known range-energy curve for aluminum given in Ref. 2. This curve is based on the Livingston-Bethe curves (1) at low energy, and on the calculations of Smith (3) above 15 Mev; the integration constant R_0 in Eq. (4) was obtained by making the range at a given energy agree with experiment. However, at proton energies below about 1.5 Mev, Eq. (1) is no longer valid, due to charge exchange phenomena involving repeated capture and loss of electrons by the proton as it nears the end of its path. As yet, no adequate theory to account quantitatively for the manner in which this affects the energy loss has been developed. Consequently, since the lower energy limit for the integration of (4) is essentially fixed at 1.5 Mev, this method is not accurate for proton energies below 1.5 Mev.

In the case of electrons, this method is not valid. Nelms (4) has calculated RSP range values for electrons in various materials by means of Eqs. (2) and (3). However, it must be remembered that such range values represent actual path lengths, which for electrons are appreciably greater than the actual thickness of absorber material required to stop the electrons.

Measurement of $-dE/dx$ and Calculation of R_{RSP}

The second approach involves an experimental measurement of $-dE/dx$, followed by integration according to (3) or (4) to give R_{RSP}. Because of the failure of Eq. (1) in the low energy region, this method has found application in the determination of proton range-energy relationships at low energies. (See Ref. 5 for a summary of data available up to about 1958.) Problems arise when no experimental data at low energies are available for the integration constant R_0. In the case of aluminum, Whaling (5) has estimated R_0 at a proton energy of 100 kev by utilizing an empirical relationship between stopping power and energy derived from experimental measurements in gases at low proton energies. In the present paper, for the sake of comparison, the reciprocal stopping power vs energy curve is extrapolated to zero energy, and Eq. (3) is used rather than (4). Although this unavoidably introduces some error into the graphically integrated value of R, the error is small, and probably no greater than that resulting from Whaling's approximation of R_0.

Since experimental measurements of $-dE/dx$ for electrons have been few, this method has not been utilized for calculating R_{RSP} for electrons.

Direct Range Measurement

In the third method the range is measured directly, by determining the thickness of absorber necessary to stop the particles. For low energy protons, range measurements in solids are scarce. In Al, for example, the only measurements below 1 Mev are those of Parkinson, Herb, Bellamy, and Hudson (6), made in 1937. Although doubt has been expressed as to the accuracy of their results (7), and although their measurements give extrapolated rather than mean range values, a comparison of their data with calculated values shows surprisingly good agreement (as will be seen below). For protons above 1 Mev, the range measurements in aluminum of Bichsel (8) in 1958 are the most recent.

For electrons, the range-energy relation given by Katz and Penfold (9) for Al is probably the most accurate; it is based on all available experimental data up to 1951, for both monoenergetic electrons and β-rays.

PROCEDURE USED IN PRESENT REPORT

Since no energy loss data or range-energy relationships have been reported for either Si or SiO_2,* the procedure used in this report has been to calculate the necessary data from available data on Al and O_2.

For protons, experimentally measured ranges in Al are available in the 1 to 30 Mev energy region (8), and calculated ranges up to 100 Mev (3). From 0.1 to 1 Mev, calculated range data have been reported by Whaling (5); as a check on his data in this energy region, the range values are recalculated in this report by a different method, in which the reciprocal of the experimentally measured stopping power is plotted vs energy, the curve extrapolated to zero energy, and the area under the curve integrated graphically to give the RSP range according to Eq. (3).

If the range is assumed to be inversely proportional to the mass stopping power, then the range of protons in Si is obtained very simply from the relation

$$\frac{R_{Si}}{R_{Al}} = \frac{{}_m(dE/dx)_{Al}}{{}_m(dE/dx)_{Si}} . \tag{5}$$

For nonrelativistic protons, the relative mass stopping power of two materials is given by the ratio

$$\frac{{}_m(dE/dx)_1}{{}_m(dE/dx)_2} = \frac{Z_1 A_2 (\ell n\, 2mv^2 - \ell n I_1)}{Z_2 A_1 (\ell n\, 2mv^2 - \ell n I_2)} . \tag{6}$$

This neglects binding effects. However, in comparing Al and Si, two neighboring elements in the periodic table, it is not expected that this will produce any significant effects in the ratio. If average excitation potentials I of 150 ev and 157 ev are taken for Al and Si, respectively, then the mass stopping power of Al relative to that of Si for 1-Mev protons is 0.97, as calculated from Eq. (6).

*RSP ranges for electrons in silicon have been calculated by Nelms (4), but these suffer the disadvantage pointed out above in that the values obtained are always greater than the actual ranges.

In order to calculate proton ranges in SiO_2, it is first necessary to calculate the mass stopping power of this compound. This was done by averaging the energy loss in the elements Si and O_2, weighted in proportion to the fraction by weight of each element in the compound:

$$ {}_m\left(-\frac{dE}{dx}\right)_{SiO_2} = 0.467\ {}_m\left(-\frac{dE}{dx}\right)_{Si} + 0.533\ {}_m\left(-\frac{dE}{dx}\right)_{O_2} \tag{7} $$

where 0.467 = wt fraction of Si in SiO_2 and 0.533 = wt fraction of O in SiO_2. The mass stopping power of Si was calculated from Eq. (6) and the known mass stopping powers of Al. The mass stopping power ratio of (6) changes slightly with proton energy; this was taken into account in calculating ${}_m(-dE/dx)_{Si}$. The mass stopping power values for O_2 were taken from the literature. Range-energy data for SiO_2 were then calculated by plotting reciprocal values of ${}_m(-dE/dx)$ SiO_2 vs energy, extrapolating the curve to zero energy, and integrating graphically (Fig. 3). The extrapolated portion of the curve is shown as a dotted line.

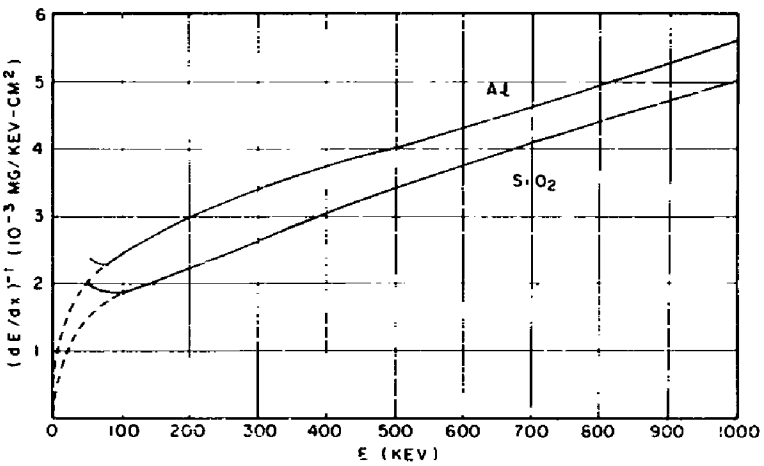

Fig. 3 - Reciprocal stopping power vs proton energy below 1 Mev

For electrons, range-energy data for both Si and SiO_2 are also based on experimental data obtained on Al. Usually, if the thickness of absorbing material is expressed in mass per cm^2, the range is taken to be independent of the nature of the material. Strictly speaking, however, this is not quite true, since the stopping power of a material is proportional to the number of electrons per gram, i.e., to Z/A. If the range of electrons in a material is taken to be inversely proportional to the ability of that material to stop electrons (i.e., to the number of electrons per gram), then

$$ \frac{R_{Si}}{R_{Al}} = \frac{(Z/A)_{Al}}{(Z/A)_{Si}} = 0.96. \tag{8} $$

Measured data for absorption of electrons in Al were corrected by this factor to give range-energy data for electrons in Si. Since SiO_2 has the same number of electrons per gram as Si, then R_{SiO_2} was taken as equal to R_{Si}. This correction factor of 0.96 may be compared to the value of 0.97 obtained from the RSP electron ranges calculated by Nelms (4) for Al and Si.

RESULTS

Protons

Range-energy data for low-energy protons (<2 mev) in Al are given in Table 1. Column 2 lists the experimental values of $(-dE/dx)_m$, taken from Table III-7 of Allison and Warshaw (10). The reciprocal values of these stopping powers are plotted in Fig. 3, and the values of R_{RSP} obtained by graphical integration of the area under this curve after extrapolation to zero are listed in column 3 of Table 1. For comparison, the calculated R_{RSP} values of Whaling (5) and the early values of R_{ex} measured by Parkinson and co-workers (6) are shown in columns 4 and 5. Considering the uncertainties involved in estimation of the range values at 100 kev by both this author (extrapolation of the RSP curve to zero energy) and Whaling (use of an empirical relation found from low energy stopping powers for protons in rare gases), the agreement is as good as could reasonably have been anticipated.

Range-energy data reported in the literature for high-energy protons in Al are shown in Table 2. Column 2 gives the experimentally determined ranges reported by Bichsel (8), and column 3 the calculated values reported by Smith (3).

Table 1
Range-Energy Data for Low-Energy Protons in Al

E (kev)	-dE/dx* (kev-cm²/mg)	R (mg/cm²)		
		Present Work†	Ref. 5†	Ref. 6‡
100	416	0.20	0.26	0.20
200	334	0.46	0.51	0.47
300	293	0.77	0.80	0.79
400	268	1.11	1.13	1.13
500	250	1.49	1.50	1.51
600	233	1.90	1.91	1.93
700	217	2.34	2.35	2.38
800	202	2.82	2.83	2.87
900	190	3.33	3.34	3.38
1000	177	3.87	3.89	3.93
2000	112	11.3	11.2	11.3

*Experimental stopping powers, taken from Table III-7, Ref. 10.

†Calculated path lengths, based on reciprocal stopping power values.

‡Experimentally measured values, based on extrapolation of number-energy curves (for fixed absorber thicknesses) to zero transmission of protons.

Table 2
Range-Energy Data for High-Energy Protons in Al

E (Mev)	R (mg/cm^2)	
	Ref. 8*	Ref. 3†
1	3.84	3.45
1.5	7.30	6.69
2	11.53	10.8
2.5	16.43	15.6
3	22.07	21.0
3.5	28.39	27.3
4	35.40	34.5
5	51.43	50.3
6	70.04	69.1
7	91.15	90.0
8	114.7	113.2
9	140.6	138.8
10	168.6	166.7
12	232.2	229.0
15	343.9	339.3
20	572.8	565
30	1183.7	1157
40	-	1933
50	-	2878
70	-	5240
100	-	9854

*Experimentally determined ranges.
†Theoretically calculated path lengths, based on the Livingston-Bethe curves below 15 Mev, and on the calculations of Smith above 15 Mev.

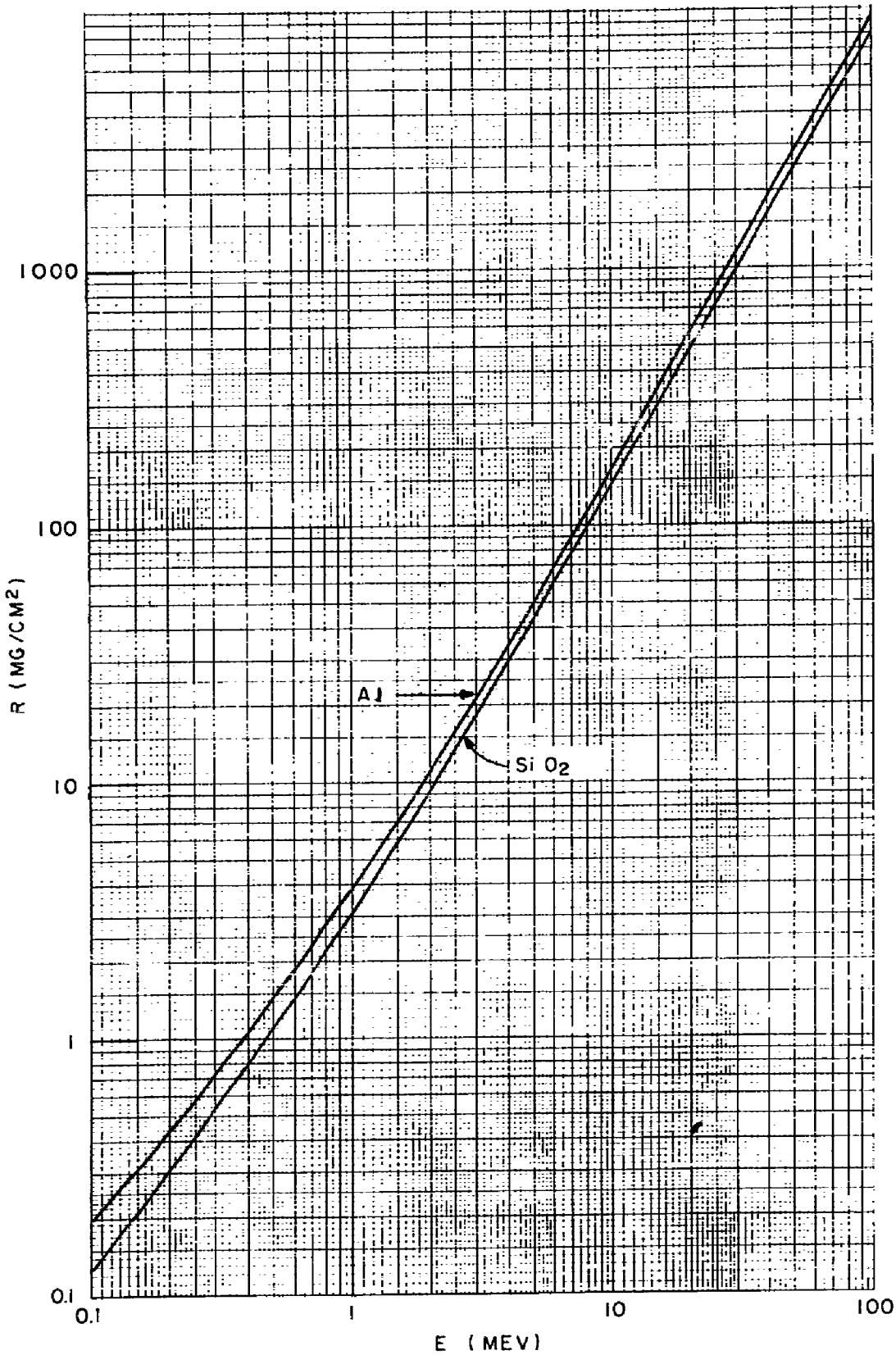

Fig. 4 - Range-energy relationship for protons (data from 1 to 30 Mev from Ref. 8; data above 30 Mev from Ref. 3)

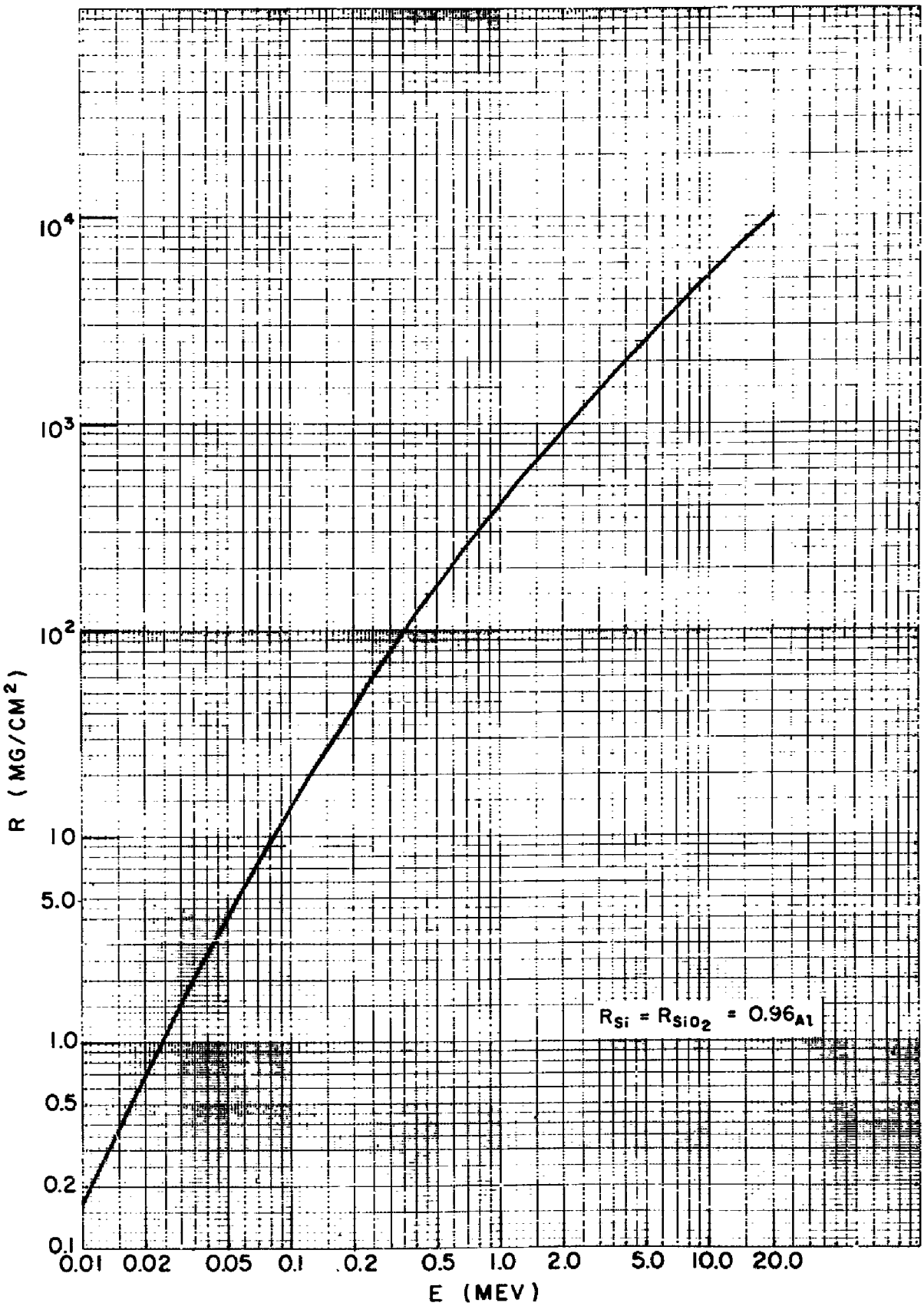

Fig. 5 - Range-energy relationship for electrons in aluminum (from Ref. 9)

Figure 4 gives the range-energy relationship for protons in Al from 0.1 to 100 Mev. In plotting this curve, data for energies below 1 Mev were taken from column 3 of Table 1; data between 1 Mev and 30 Mev from column 2 of Table 2, and data above 30 Mev from column 3 of Table 2.

To obtain range values for protons in Si, the range in Al as read from Fig. 4 should be multiplied by 0.97, the ratio of the mass stopping power of Al relative to that of Si (see Eq. 5). No attempt was made to draw the curve for Si because it lies so close to that for Al.

Range-energy data for SiO_2 were obtained by calculating first the mass stopping power according to Eq. (7). Data used for this calculation were the $_m(-dE/dx)_{Si}$ values obtained by applying the corrective term from Eq. (6) to $_m(-dE/dx)_{Al}$ data, and the energy loss data for gaseous oxygen. The $_m(-dE/dx)$ data for oxygen were obtained from Table III-11 in Ref. 10 for energies up to 1 Mev, and from Table V in Ref. 11 for energies greater than 1 Mev. Reciprocal stopping powers for SiO_2 were then plotted vs energy, the curve extrapolated to zero (Fig. 3), and the integration according to Eq. (3) carried out graphically. The range values thus obtained are plotted in Fig. 4.

Electrons

For reasons previously given, range-energy relationships for electrons are best obtained experimentally. Katz and Penfold (9) have summarized very ably the work in this field up to 1951. Based on all available data, both on monoenergetic electrons and β-rays, they arrived at the following empirical relationships between the range in Al expressed in mg/cm^2 and the electron energy expressed in Mev:

$$R = 412\,E^n, \qquad \text{for} \qquad 0.01\ \text{Mev} < E < 3\ \text{Mev} \tag{9}$$

where $n = 1.265 - 0.0954\ \ell n\ E$, and

$$R = 530\,E - 106, \qquad \text{for} \qquad 3\ \text{Mev} < E < 20\ \text{Mev}. \tag{10}$$

The range-energy relationship given by these functions is plotted in Fig. 5, which is the same as Fig. 2 in Katz and Penfold.

To obtain range values in Si, figures read from this curve should be multiplied by 0.96 (see Eq. 8). Range values in SiO_2 are the same as in Si.

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